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Search for filamentary accretion through low velocity shocks

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Filamentary star formation

Herschel observations revealed the ubiquitous presence of interstellar filaments and their importance in star formation (e.g. [1],[2],[3]). It is proposed that they form by dissipation of kinetic energy in large scale magnetohydrodynamic flows through low-velocity magnetised shocks (C-shocks) and then fragment in prestellar cores after reaching a density threshold of ~ 16 $M_\odot$/pc [4],[5].
There are indications that these filaments accrete mass through inflow of matter from the sides along the magnetic field (e.g. [6],[7]). **However, direct evidence of such shocks is vital to confirm this scenario**.

Excess in observations of mid-J CO lines

Some promising mid-J CO excess in nearby clouds and a distant IRDC was interpreted as turbulence dissipation from low-velocity shocks [8],[9],[10]. But there is the need to clearly associate this finding with dense structure formation.

Things to keep in mind when looking for turbulence dissipation shocks:

- Excess emission can also arise from photodissociation regions (PDRs)
- Both PDR and shock models are still uncertain (e.g., chemistry)
- There can be confusion with low-velocity shocks related to protostars

It is thus mandatory to look for these accretion shocks in a controlled direction which is free of protostars and where filamentary accretion is expected.

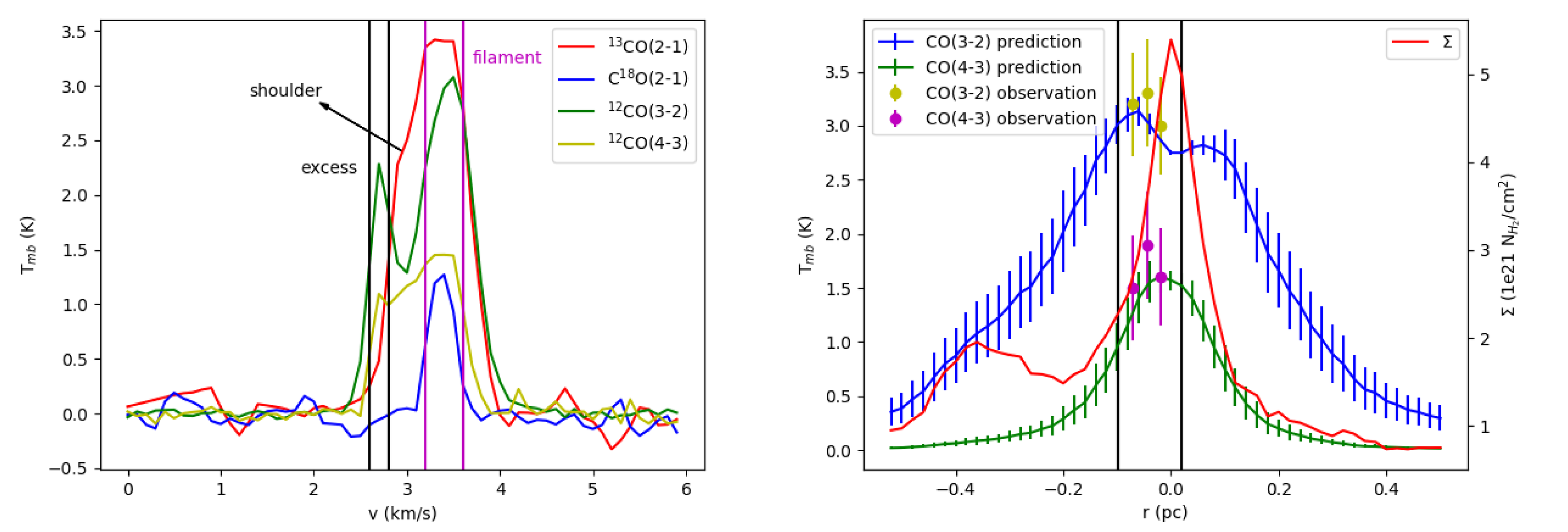

Fig 3) Left: The lines observed with APEX, here averaged over the northern map, show an excess component in CO(3-2) and CO(4-3). **Right:** In red the column density profile obtained from Herschel at the northern position. The blue and green profiles show the expected line intensity for CO(3-2) and CO(4-3) based on the column density and temperature profile from Herschel. This was predicted using RADEX [13]. In yellow and magenta: the observed CO(3-2) and CO(4-3) intensities of the filament component with APEX. The vertical black lines indicate the area imaged with APEX.

APEX: FLASH observations

CO(3-2) and CO(4-3) were imaged with FLASH at 2 positions slightly off the crest of Musca (red boxes in **Fig 2**). This can be compared with ^{13}CO(2-1) and C^{18}O(2-1) pointings towards Musca [12] to look for indications of shocks.

This comparison shows CO(3-2) and CO(4-3) spectra with two components, shown in **Fig 3**, which cover the entire mapped area at both positions.
One component corresponds to the ^{13}CO(2-1) and C^{18}O(2-1) peak (filament). The second component has no correspondance (excess).
There is also a ^{13}CO(2-1) shoulder, which has a large $\frac{\mathrm{CO(4\text{-}3)}}{\mathrm{CO(3\text{-}2)}}$ ratio.

Filament + warm excess

We focus on the map in the north with a clean separation of the filament and excess components.
The intensities obtained for the filament component agree with RADEX estimates based on the Herschel column density and temperature profile, assuming a central gas temperature of 8.5 K (**Fig 3**).

RADEX setups also provide consistent results for the excess, see **Fig 4**:
- warm: generally > 60 K, and possibly even > 150 K.
- low ^{12}CO column density: 3e14 /cm^{-2} < $\Sigma_{^{12}CO}$ < 8e14 /cm^{-2}
- H_2 density: > 10^3 cm^{-3}

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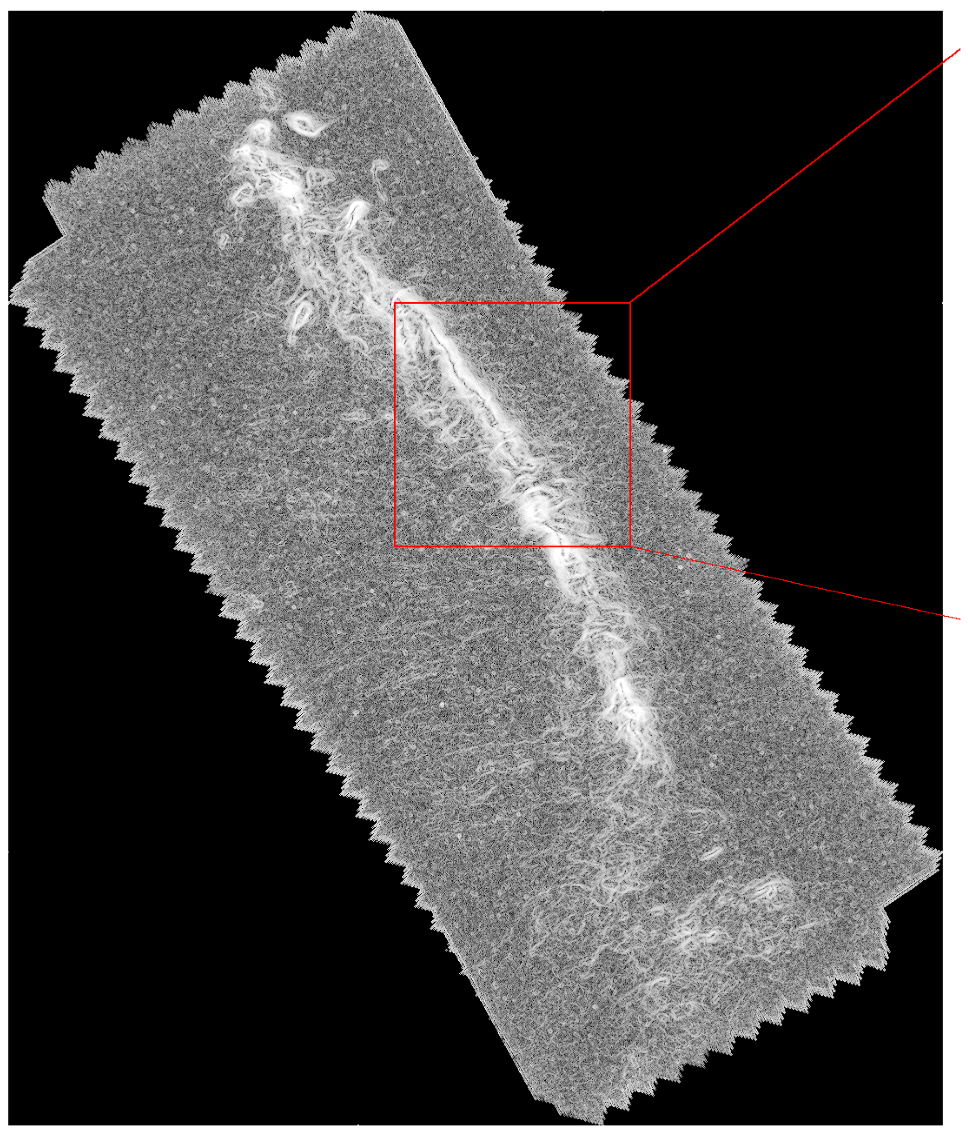

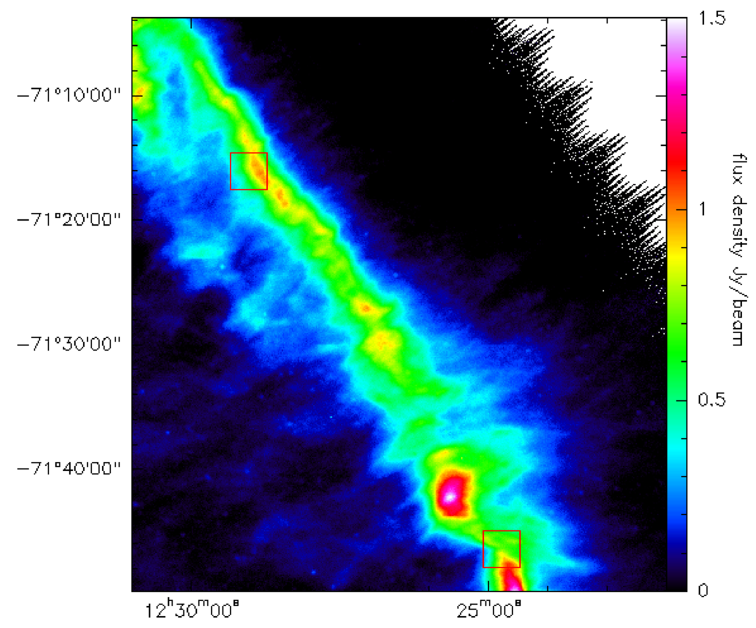

Fig 2 (above): A part of the Herschel 250μm map of Musca [7]. The two red boxes are the 2' x 2' maps that were observed with APEX to look for indications of shocks.

Fig 1 (left): The map for Musca obtained with the INRIA/Geostat analysis tool, where the white areas have singular local behaviour. This singular behaviour is observed along the entire Musca filament.

Musca: Singularities in non-linear local analysis

A good candidate for the detection of such accretion shocks is **Musca**.
It is a nearby filament that is free of protostars and located in a region with an expected low UV radiation field. The filament also shows indications of inflow from the sides along the magnetic field via a network of striations and strands [7].
So in the proposed scenario, it should have such low-velocity accretion shocks with low PDR confusion and no confusion from protostellar outflow.
A non-linear local gradient analysis tool developed by the Bordeaux INRIA/Geostat team established singular areas along the entire Musca-filament compared to the normal behaviour of the multifractal structure of the region (**Fig 1**).
Proposed interpretation: turbulence dissipation due to filamentary accretion shocks [11].

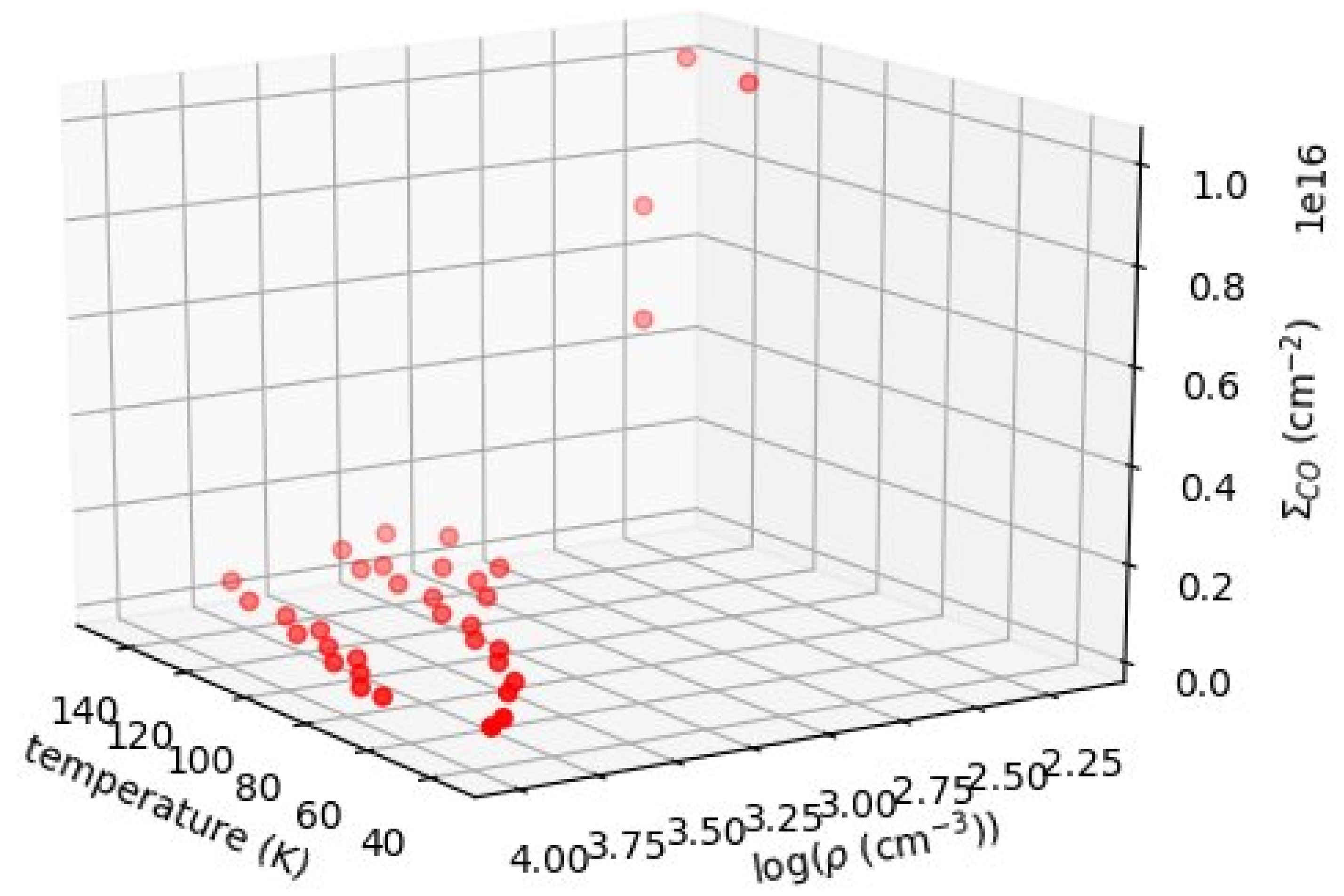

Fig 4) RADEX input that is consistent with both CO(3-2) and CO(4-3) emission of the excess component while keeping the ^{13}CO(2-1) and C^{18}O(2-1) emission sufficiently low.

Excess: PDR or shock?

What is the origin of the CO excess emission: PDR or shock?
- Seen at both positions, it could be a PDR over the entire cloud. But shocks should also occur along the entire filament.
- RADEX suggests a layer with a relatively high density (> 10^3 cm^{-3}) and temperature (> 60 K). This might fit better with shocks.
- The narrow linewidth of the excess could be an interesting result for shocks.
- What is the reason for the velocity offset of the excess and the shoulder: decelerating layer at the surface of the filament?

TO DO: a direct comparison with shock and PDR models, combine with scheduled SOFIA observations of low-velocity shock tracers, obtain a larger CO(3-2) and CO(4-3) map,...
If the CO excess emission is the result from shocks: a clean detection of filament formation through low-velocity shock dissipation of supersonic turbulence.